Ising Quantum Hall Ferromagnet in Magnetically Doped Quantum Wells

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We report on the observation of the Ising quantum Hall ferromagnet with Curie temperature T_C as high as 2 K in a modulation-doped (Cd,Mn)Te heterostructure. In this system field-induced crossing of Landau levels occurs due to the giant spin-splitting effect. Magnetoresistance data, collected over a wide range of temperatures, magnetic fields, tilt angles, and electron densities, are discussed taking into account both Coulomb electron-electron interactions and s−d coupling to Mn spin fluctuations. The critical behavior of the resistance "spikes" at $T \rightarrow T_C$ corroborates theoretical suggestions that the ferromagnet is destroyed by domain excitations.

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Over the last several decades two-dimensional electron systems (2DES) have emerged as a principal medium for studying phenomena driven by many-body correlation effects since the carrier density and the relative strength of orbital and spin effects can be controlled externally. Owing to the quenching of the kinetic energy, correlation effects are particularly strong in the magnetic field leading to an unexpectedly rich variety of ground states and quasiparticle forms [1]. In particular, if Landau levels (LLs) corresponding to the opposite spin orientations of quasi-particles at the Fermi level overlap, the spin degree of freedom is *not* frozen by the field so that a spontaneous spin order may appear at low temperatures [2], the resulting state being known as the quantum Hall ferromagnet (QHFM). Importantly, the ground state is predicted to have the uniaxial anisotropy if the spin subbands involved originate from different LLs [3]. The level arrangement corresponding to such an Ising QHFM has been realized in various III-V 2DES [4, 5].

In this Letter we present results of experimental studies, which demonstrate the existence of a QHFM in a quantum well (QW) containing magnetic ions. In our modulation-doped n-type (Cd,Mn)Te structures, owing to the mean-field part of the s−d exchange interaction between the electrons and Mn spins, the spin-splitting of electronic states is not only giant but depends, in a nonlinear fashion, on the magnetic field B. Accordingly, many crossings of Landau spin sublevels occur, even without tilting the field direction. The ferromagnetic ordering gives rise to the presence of hysteresis and resistance "spikes", making it possible to determine the phase diagram of a QHFM as a function of the carrier density and tilt angle. Critical behavior of the spike resistance is found, verifying the recent theoretical prediction [6]. At the same time, the Curie temperature T_C is shown to reach 2 K, a value much higher than that observed and explained theoretically in the case of both (i) high electron mobility AlAs QW in the quantum Hall effect (QHE) regime ($T_C \lesssim 0.5$ K [5, 6]) and (ii) n-type diluted magnetic semiconductor (DMS) at $B = 0$ ($T_C \lesssim 0.2$ K in (Zn,Mn)O:Al epilayers [7]). This enhanced stability of the QHFM phase is rather surprising in view of both previous results [5, 6] and the significance of disorder in the present material. It is discussed in terms of electron-electron interactions [3] as well as by considering the role of static and dynamic fluctuations in the subsystem of the Mn spins.

Previous magnetotransport studies of 2DES containing a DMS channel have demonstrated that the Mn spins have no effect on the precision of the Hall resistance quantization [8, 9, 10]. Furthermore, the high degree of spin polarization has made it possible to verify the temperature and size QHE scaling up to the filling factor as high as $\nu = 8.5$ [10], avoiding uncertainties associated with the overlap of spin-split LLs. However, some anomalies of the QHE, which were absent in CdTe QW, have been noted in these studies [10]. In view of the present results, they were assigned correctly to crossings of LLs.

The modulation-doped (Cd,Mn)Te QW was grown for the present study by molecular beam epitaxy, exploiting the previous expertise [10, 11] on how to obtain 2DES with an adequate carrier density and mobility in a QW with a sizable effective Mn concentration. Barriers of $Cd_{0.8}Mg_{0.2}Te$ were separated from (001) undoped GaAs substrate by 1 nm ZnTe and 3 μm CdTe buffer layers. The Mn ions were inserted into the QW by the digital alloy technique, that is by depositing three evenly spaced monolayers of $Cd_{1-x}Mn_xTe$ during the growth of CdTe QW with the thickness $L_W = 10$ nm, as depicted schematically in the inset to Fig. 1(a). According to the spectral position of the photoluminescence line at 77 K, average $x = 2\pm0.5\%$. The iodine donors were introduced to the front barrier at 20 nm away from the QW. For magnetotransport measurements a 0.5×1 mm^2 Hall bar was etched, to which leads were soldered with indium. A gold on chromium front gate was deposited onto cap layer, and makes it possible to control the electron density n_s between 1.6 and 3.6×10^{11} cm^{-2}, as determined by

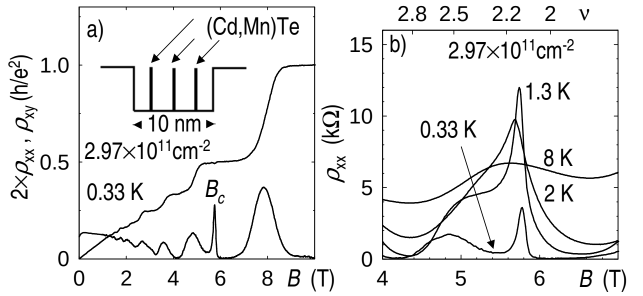

FIG. 1: (a) Resistances ρ_{xx} and ρ_{xy} at $T = 0.33$ K for $n_s = 2.97 \times 10^{11}$ cm^{-2}($V_g = 0$). Note the presence of a spike in ρ_{xx} at $B_c \simeq 5.8$ T, shown at selected temperatures in (b). Inset: the nominal distribution of magnetic monolayers in the QW.

Hall measurements at 10 and 23 K. The low-temperature electron mobility, limited to a large extent by short-range alloy and spin disorder scattering, is about $\mu = 1.6 \times 10^4$ cm^2/Vs. The experiments were performed in magnetic fields up to 18 T and down to temperature T of either 0.24 K in a pumped ^{3}He system or 0.03 K in a ^{3}He/^{4}He dilution refrigerator. In the latter, the sample can be rotated in order to change the angle θ between the interface normal and $\boldsymbol{B}$.

Figure 1(a) presents the Hall ρ_{xy} and the longitudinal ρ_{xx} resistivities, the latter revealing the presence of a strong resistance "spike" in the magnetic field $B_c \approx 5.8$ T, which corresponds to the LL filling factor $\nu \equiv n_s h/eB \approx 2$. According to Fig. 1(b) the ρ_{xx} anomalies peak around 1.3 K. Moreover, at the same T a dramatic shift of the Shubnikov-de Haas (SdH) maxima is clearly visible in Fig. 1(b). Figure 2(a) shows, in turn, that $B_c \cos\theta$ decreases when θ increases. Guided by the previous experimental [5] and theoretical [6] results, we presume that the spikes appear at the crossing points of spin sublevels. In order to evaluate the field values B_c at which crossings are expected in our system, we start from the known form of the LL energy in DMS [12],

$$E_{n,\uparrow,\downarrow} = (n + 1/2)\hbar eB\cos\theta/m^* \pm \\ \pm\frac{1}{2}\left[g^*\mu_B B + \alpha N_0 x_{eff} S \mathrm{B}_S\left(\frac{g\mu_B B}{k_B[T+T_{AF}]}\right)\right]. \quad (1)$$

Here n is the LL index; $m^* = 0.10m_0$ and $g^* = -1.67$ [13] are the effective mass and Landé factor of the electrons in CdTe; $\alpha N_0 = 0.22$ eV is the s$-$d exchange energy [12, 14], and B_S is the Brillouin function, in which $S = 5/2$ and $g = 2.0$. The functions $x_{eff}(x) < x$ and $T_{AF}(x) > 0$, known from extensive magnetooptical studies of uniform $Cd_{1-x}Mn_xTe$ layers [14], describe the reduction of magnetization $M(T,H) = g\mu_B x_{eff} N_0 S \mathrm{B}_S(T,H)$ by antiferromagnetic interactions.

The crossing occurs at $E_{1,\downarrow} - E_{0,\uparrow} = \varepsilon(B\cos\theta)$, where ε is an energy correction brought about by an electron exchange interaction with the occupied $0\downarrow$ LL. We take

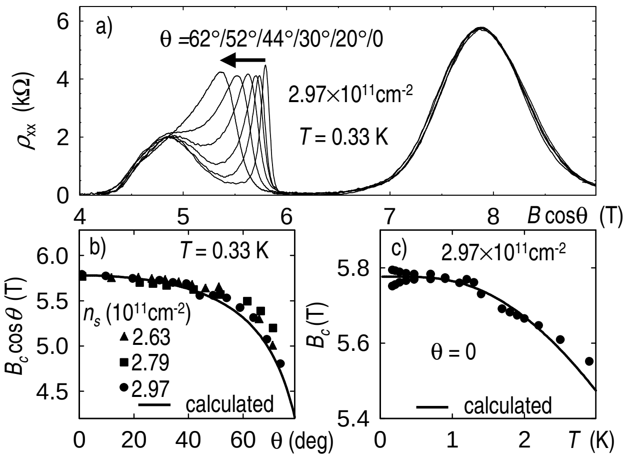

FIG. 2: (a) Resistance ρ_{xx} for $n_s = 2.97 \times 10^{11}$ cm^{-2} for various tilt angles θ (a). Experimental and calculated (Eq. 1) spike positions (b,c) for two directions of the field sweep (c).

ε in the form determined experimentally [5] and theoretically [6] for the AlAs QW, ε[K] $= 2.32 + 1.79B\cos\theta$[T]. As shown in Figs. 2(b) and 2(c), we obtain a remarkably good description of the spike positions B_c, with one adjustable parameter, the Mn concentration x set at 1.37%, for which $x_{eff} = 1.12\%$ and $T_{AF} = 0.47$ K.

The interpretation of the resistance spikes in terms of the QHFM formation implies that they should disappear if ν deviates from an integer at B_c. This is clearly demonstrated in Fig. 3(a), where $\rho_{xx}(B)$ is presented for various gate voltages V_g, corresponding to $1.65 \leq \nu \leq 2.45$ at $B_c = 5.8$ T. A number of important conclusions emerges from these data. First, in contrast to the SdH maxima, the spike positions do not depend on V_g, which substantiates the assignment of the spikes to the level crossing and rules out macroscopic nonuniformities of the 2DES as their origin. Second, the spike amplitude peaks at $\nu = 2 \pm 0.02$, and it decreases for both smaller and higher ν values, as shown in the inset to Fig. 3. Finally, a careful examination of the evolution of $\rho_{xx}(B)$ plots with V_g makes it possible to detect spikes at other field values and, by making use of the fan chart depicted in Fig. 3(b), to identify indices of the relevant LLs.

Having established that the spikes occur if LLs cross at ν close to integers, we turn to experimental results which demonstrate the existence of a phase transition at nonzero temperatures under such conditions. According to Fig. 4(a), the spike magnitude exhibits a rather sharp maximum at the temperature that we identify as T_C. At the same time, a hysteresis loop of $\rho_{xx}(B)$ develops when B is swept in two directions below T_C, as presented in Fig. 4(b). Hence, our results corroborate the notion [3] that if ν is close to an integer at B_c, a transition to the Ising QHFM ground state takes place. In this broken symmetry state, all electrons fill up one LL, leaving the other LL empty. This is evidenced in Fig. 1(b) which

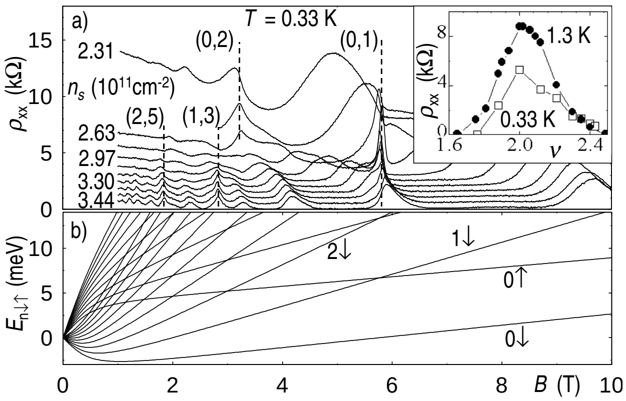

FIG. 3: (a) Resistance ρ_{xx} at 0.33 K for $n_s = 2.31 - 3.44 \times 10^{11}$ cm^{-2}. Traces are shifted vertically for clarity. Dashed lines mark resistance spikes at the crossing of LLs with the indices (2,5), (1,3), (0,2), and (0,1) as determined from LLs energies displayed in (b). The inset shows the height of the spike at $B_c \simeq 5.8$ T as a function of the filling factor.

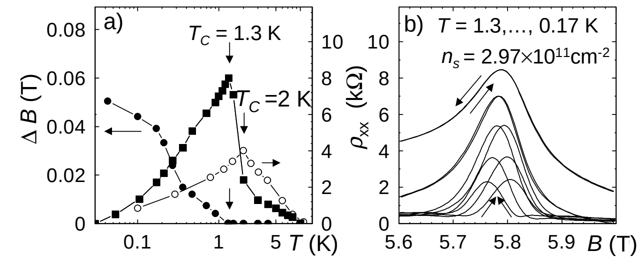

FIG. 4: (a) The spike height as a function of T for $n_s = 2.97$ (squares) and 2.54×10^{11} cm^{-2} (open circles). If the spike and the SdH peak overlap, the contribution of the latter is subtracted. Full circles show the width of hysteresis loops presented in (b), where $\rho_{xx}(B)$ is depicted in the region of the spike for two directions of the field sweep at various T. The sweep rate is 0.3 T/min. The resistance behavior, reminiscent of critical scattering, and the presence of magnetic hysteresis are taken as evidences for the phase transition to QHFM.

reveals the absence of a SdH maximum at B_c below T_C. However, depending on a local potential landscape either $0\uparrow$ or $1\downarrow$ LL is filled up in a given space region. Domain walls appearing in this way form edge-like channels. Their presence gives raise to an additional conductance that results in the resistance spike at B_c [6].

The collective nature of the phenomenon observed here points to a minor importance of the one-electron anticrossing effect driven by spin-orbit interactions [15] or spin-flip scattering by Mn ions. Above T_C, in turn, the carriers are distributed among two degenerated subbands, which means that the Fermi level resides in the vicinity of the DOS maximum at B_c. Thus an additional SdH peak appears at $T > T_C$, as shown in Fig. 1(b), a genuine one electron effect, examined recently in (Zn,Cd,Mn)Se QWs [16].

In order to discuss mechanisms that may control the magnitude of T_C in our system, we begin with the s−d exchange interaction. According to the mean-field theory of magnetic polarons and Zener's ferromagnetism [17, 18] we expect the gain of the free energy per one electron associated with the formation of the QHFM state to be given by

$$J_S = \frac{\alpha^2}{2k_B(2g\mu_B)^2}\int d\boldsymbol{\rho}\int dz\chi_{\parallel}(z)|\psi(\boldsymbol{\rho})\varphi(z)|^4. \quad (2)$$

Here, $\chi_{\parallel} = \partial M/\partial H$ is the longitudinal susceptibility of the Mn spins inside the QW and the integral over $|\psi(\boldsymbol{\rho})\varphi(z)|^4$ is the inverse participation volume P. Recent work on the Knight shift of Mn spin resonance in a similar (Cd,Mn)Te QW [19] provides information on P. Importantly, the Mn spin resonance was detected resistively, which means that only those Mn spins that are coupled to the electrons participating in the charge transport were probed. The data, taken at low T, where motional narrowing ceases to be important, point to a sevenfold enhancement of P^{-1} for $\nu = 3$ over the value expected for the uniform distribution of the electrons in the QW. In spite of this enhancement, we find that J_S is rather small, $J_S \approx 0.02$ K at 2 K and at 5.8 T, and decreases even further when T decreases. Another modeling of $\chi_{\parallel}$, for instance by adding a contribution from the magnetization step due to the nearest neighbor Mn pairs [20], increases J_S by no more than a factor of two. We note also that the application of B, which saturates the Mn spins, $Sg\mu_B B \gg k_B(T + T_{AF})$, shifts the Mn excitation spectrum to energies greater than k_BT. Since in this regime the Mn spins fluctuate faster than the electronic spins, the s−d coupling can be regarded as mediating interactions among the itinerant electrons [21]. In such a case, the contribution of quantum fluctuations to J_S becomes important, which further increases $\chi_{\parallel}$ in Eq. (2) in the limit $T \to 0$ [17]. Though the exact value of the enhancement factor is unknown, we claim nevertheless that the s−d coupling does not give the quantitatively important contribution to the QHFM stability. Accordingly, our results can be employed directly to test the existing theoretical predictions on the QHFM stability [3, 6] in the presence of disorder [22, 23].

We compute the gain in the energy associated with the formation of the QHFM state $J = U_{zz}/2$ from the Hartree-Fock theory [3], in which effects of remote LLs are neglected. For the (Cd,Mn)Te dielectric constant $\epsilon = 10$ and the envelope function in the form $\varphi(z) = (2/L_W)^{1/2}\cos(\pi z/L_W)$, we obtain $J \approx 12$ K per electron at B_c, whereas $J \approx 18$ K in the limit $\varphi(z) = \delta(0)$. The value of J is therefore ten times larger than the one-electron anticrossing energy observed in a similar QW by optical absorption [24]. Since in the case of the Ising QHFM there are no skyrmion excitations [23], the effect of disorder can be evaluated within the mean-field approach [22]. In the presence of a short-range disorder

potential, this theory [22] predicts the QHFM to occur if $J > W$, where $W = \hbar[(\pi e\omega_c/2\mu m^*)]^{1/2}/4k_B \approx 8$ K for our QW. Furthermore, it has recently been suggested [6] that the magnitude of T_C can actually be much smaller than J, as it is determined by the free energy competition between the magnetic domain configurational entropy at $T > 0$ and the energy penalty associated with the domain wall formation. Thus, T_C of 2 K that we observe is consistent with the existing theories of the QHFM [3, 6, 22]. On the other hand, the fact that this value is four times higher than that of AlAs [5, 6] appears surprising, especially if we note that the crossing of the LLs $n = 0$ and $n = 2$ (AlAs) should result in a greater J than in our case involving $n = 0$ and $n = 1$ LLs [3]. We assign the greater stability of the QHFM state in (Cd,Mn)Te to seven times larger distance to the nearest LLs at B_c (caused by larger ω_c), which leads to a significantly weaker screening of the Coulomb interaction compared to AlAs. Furthermore, it is possible that quenched spin-dependent disorder leads to an increase of the magnetic stiffness by pinning of the domains in magnetic QWs. Indeed, we evaluate the corresponding energy scale W_S to be of the order of 1 K at B_c for the randomly distributed Mn ions. Within the domain formation scenario [6], the resistance spikes correspond to the enhancement of conductance due to electron transport along the domain walls, whose total length diverges at $T \to T_C^-$ in a narrow field range corresponding to the demagnetized state [6]. Thus, the critical behavior of the spike observed by us provides an important experimental support for this model of the spike origin.

In conclusion, our results demonstrate that the presence of the magnetic ions allows one to reach conditions for the observation of the Ising quantum Hall ferromagnet. Our data, taken over a wide range of the parameter space, have provided the important verification of the recent theory of this phase [3] and for the mechanism of the spike formation [6]. The arguments have been put forward indicating that the Mn spin fluctuations give rise to an additional electron-electron interaction and constitute domain pining centers. It appears at this point, however, that the Coulomb interaction dominates and makes the QHFM state more stable than anticipated previously.

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